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Major Goals: The objective of this project is to investigate the molecular beam epitaxial (MBE) growth and properties of InGaN/GaN dot-in-nanowire heterostructures. The nanowire arrays will be grown by the technique of selective area epitaxy, which can offer a precise control of the size, spacing, and emission wavelength. By optimizing the size and quantum-confinement and by incorporating core-shell structures, we aim to achieve InGaN dot-in-nanowire arrays with high luminescence efficiency. Moreover, the design and fabrication of InGaN nanowire lasers will be investigated. Work in this project will enable an unprecedented understanding of the selective area epitaxy, and optical and electronic properties InGaN dot-in-nanowire heterostructures and the realization of a new generation of high performance semiconductor lasers for both short-reach and on-chip optical interconnects.

Accomplishments: We have performed a detailed study of the epitaxy and properties of InGaN/AlGaN dot-in-nanowire core-shell heterostructures. We have further demonstrated a green laser diode using these nanostructures. Major accomplishments are detailed in the attached report.

Training Opportunities: PhD student Kishwar Mashooq has been trained in the epitaxy and optical characterization of semiconductor nanostructures.

Results Dissemination: H George, Y-H Ra, Z Mi, T Norris, "Carrier relaxation dynamics of InGaN/GaN dot-in-nanowires", CLEO, 2018.

Y. H. Ra, R. T. Rashid, X. H. Liu, S. Sadaf, K. Mashooq, and Z. Mi, "An Electrically Pumped Surface-Emitting Semiconductor Green Laser," Submitted.

Honors and Awards: Zetian Mi has been elected Fellow of SPIE and Fellow of OSA.

Protocol Activity Status:

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PARTICIPANTS:

Participant Type: PD/PI
Participant: Zetian Mi
Person Months Worked: 1.00 **Funding Support:**

Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Kishwar Mashooq
Person Months Worked: 3.00 **Funding Support:**
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National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Kishwar Mashooq
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Project Contribution:
International Collaboration:
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National Academy Member: N
Other Collaborators:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Yong-Ho Ra
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
International Collaboration:
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National Academy Member: N
Other Collaborators:

Project Report

1. Introduction and Project Objective

Recently, plastic optical fibers (POFs) have emerged as a low-cost alternative to the conventional connection cables and optical fibers, promising many exciting applications in short-reach connections including home networks, industrial networks, digital home appliances, automotive, remote sensing, and medical controls. To date, however, there are no optical transmitters that can meet the bandwidth, performance and cost requirements at the low POF attenuation windows near 570 nm [1], due to the lack of a mature semiconductor laser technology in the deep green and yellow wavelength range. InGaAlP/GaAs materials have been intensively studied for orange and red-emitting devices [2-4]. The achievement of high quality InGaP/InAlGaP quantum well heterostructures with strong carrier confinement has remained difficult in the yellow and orange spectral range [4]. InGaN exhibits direct energy bandgap in the range of 3.4 eV to 0.65 eV by varying alloy compositions [5]. However, the emission wavelengths of InGaN quantum well lasers have been limited to the near-ultraviolet, blue, and blue-green spectral ranges [6-8]. The challenges for realizing InGaN-based green and yellow lasers include the presence of large densities of defects and dislocations due to the large lattice mismatch (~11%) between InN and GaN [9-11], large strain-induced polarization field and the resulting quantum-confined Stark effect (QCSE), and the difficulty in realizing efficient *p*-type conduction in In-rich InGaN. Recently, significant progress has been made in InGaN nanowire heterostructures, which are virtually free of dislocation and exhibit a very small level of strain field, due to the efficient strain relaxation related to the large surface-to-volume ratio [12-18].

In this project, we propose to investigate the molecular beam epitaxial (MBE) growth and properties of InGaN/GaN dot-in-nanowire heterostructures. The nanowire arrays will be grown by the technique of selective area epitaxy, which can offer a precise control of the size, spacing, and emission wavelength. By optimizing the size and quantum-confinement and by incorporating core-shell structures, we aim to achieve InGaN dot-in-nanowire arrays with high luminescence efficiency. Moreover, the design and fabrication of InGaN nanowire lasers will be investigated. Work in this project will enable an unprecedented understanding of the selective area epitaxy, and optical and electronic properties InGaN dot-in-nanowire heterostructures and the realization of a new generation of high performance semiconductor lasers for both short-reach and on-chip optical interconnects.

2. Summary of the Most Important Results

2.1. Selective area epitaxy of InGaN dot-in-nanowire heterostructures

In this project, InGaN nanowire arrays were grown on *n*-type GaN template on sapphire substrate by radio frequency (RF) plasma-assisted MBE system using the special technique of selective area epitaxy, schematically shown in Fig. 1. *n*-GaN:Si nanocrystal arrays were first grown with a substrate temperature of 850 °C, a nitrogen flow rate of 0.4 standard cubic centimeter per minute (sccm), and Ga beam equivalent pressure (BEP) of ~2.9×10^{-7} Torr. The InGaN/AlGaN core-shell heterostructures were incorporated in the laser active region. To form the core-shell structure, first the core InGaN disk layer was grown on the top surface region of *n*-GaN nanowires. Due to the strain induced self-organization effect, the size of the InGaN disk becomes smaller than the *n*-GaN nanocrystal diameter. The incorporation of AlGaN barrier layers, instead of GaN barrier layers, leads to the formation of an AlGaN shell structure surrounding the InGaN quantum disk active region, due to the smaller Al adatom diffusion length compared to Ga and In adatom diffusion. As a consequence, the growth fronts including the top and sidewalls of the InGaN region can be covered by AlGaN layers, thereby leading to the spontaneous formation of large band-gap AlGaN shell structures. The growth conditions of InGaN/AlGaN multiple quantum disk layers included a substrate temperature of 650°C, a nitrogen flow rate of 1.2 sccm, a forward plasma power of ~ 350 W, In BEP ~8.1×10^{-8} Torr, Ga BEP ~1.8×10^{-8} Torr, and Al BEP ~4.2×10^{-9} Torr, respectively. By repeating the growth process, coaxially aligned cone-like AlGaN shell layers can be fabricated surrounding the InGaN multiple quantum disk structures, schematically shown in Fig. 2(a). The SEM image is shown in Fig. 2(b).

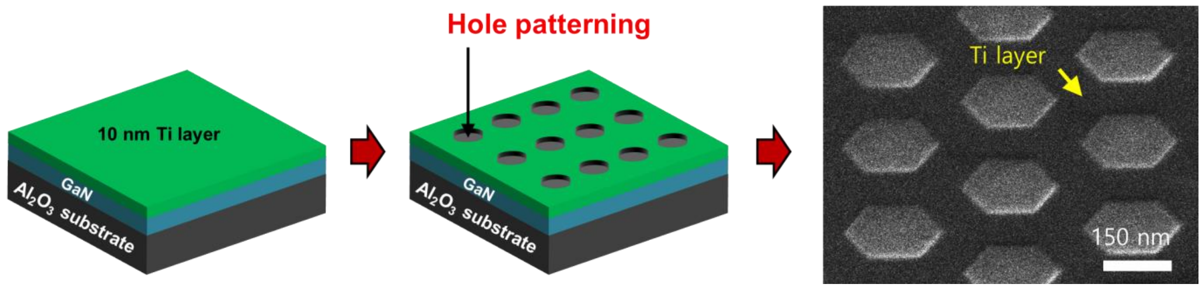
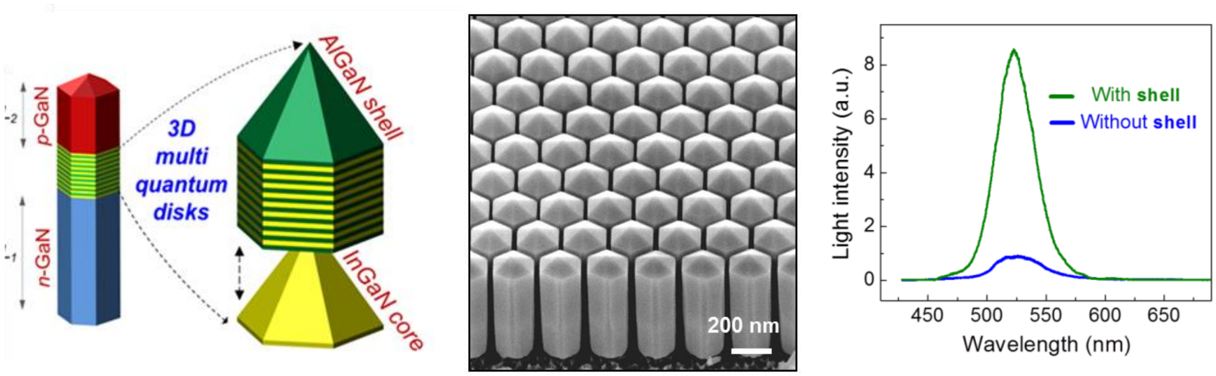


Figure 1. Schematic illustration and FE-SEM image of the patterned Ti thin film nano-hole mask fabricated on *n*-type GaN template on sapphire substrate.



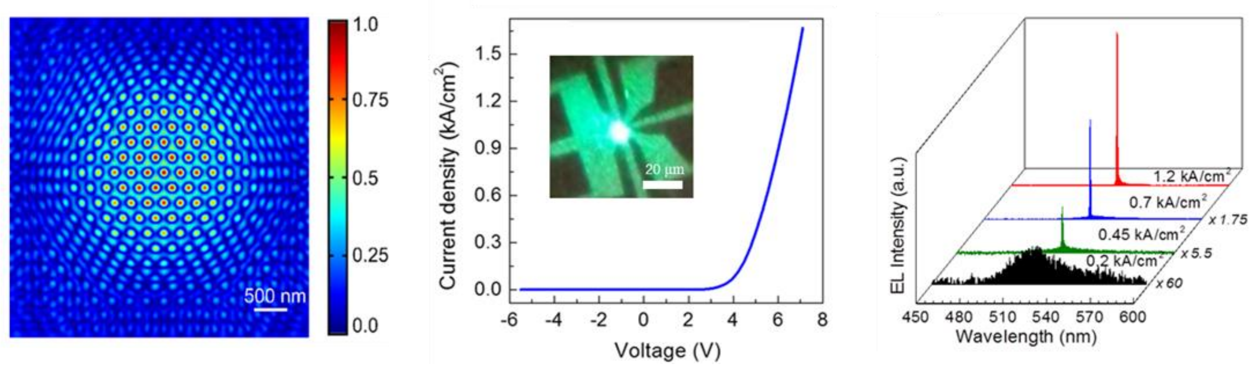
(a) (b) (c)

Figure 2. (a) Schematic of InGaN/AlGaN nanowire heterostructure, which consists of *n*-GaN cladding layer, core-shell InGaN/AlGaN multiple quantum disk active region, and *p*-GaN cladding layer. (b) Tilted-view SEM image of the InGaN nanowires. (c) Photoluminescence emission spectra of InGaN/AlGaN core–shell multi-quantum disk nanowires (green curve) and InGaN/GaN multi-quantum disk nanowires without AlGaN shell (blue curve) measured at 300 K.

Optical properties of the semi-polar InGaN/AlGaN core-shell heterostructure were studied using photoluminescence (PL) spectroscopy. Shown in Fig. 2(c) is the PL spectra measured at room temperature using a 405 nm laser as the excitation source. It is seen that the PL intensity of the semi-polar InGaN/AlGaN core-shell is enhanced by nearly a factor of eight, compared to

InGaN/GaN heterostructure without the formation of AlGaN shell. The shell structure spontaneously formed on the sidewalls of the active region can lead to drastically reduced non-radiative surface recombination due to the effective lateral confinement offered by the large band-gap AlGaN shell. Moreover, unique quasi 3D structure exhibits massively enhanced surface emission and improved carrier injection efficiency, due to the much larger active area. It is also well known that such semi-polar structure can effectively suppress the quantum-confined Stark effect (QCSE) due to the reduced polarization fields.

2.2. Electrically pumped InGaN nanowire surface emitting laser diodes



(a) (b) (c)

Figure 3. (a) The electric field profile of the band edge mode (λ = 523 nm) calculated by the 3D finite-difference time-domain method. (b) Current-voltage (I-V) characteristics of the laser device. Inset: EL image of the green lasing. (c) EL spectra measured from different injection currents under CW biasing conditions at room-temperature.

By exploiting the photonic band-edge resonant effect of the nanocrystal array, we have demonstrated an electrically injected surface-emitting green laser diode without using conventional thick and resistivity DBRs. The device operates at 523.1 nm and exhibits a low threshold current density ~400 A/cm^2 and highly stable operation at room-temperature. In this design, each nanowire consists of *n*-type GaN cladding layer (~370 nm thick), multiple InGaN quantum disk active region, and *p*-type GaN cladding layer (190 nm thick). The nanowires have a spacing ~30 nm, and the lattice constant is 250 nm. At the band edge, the low group velocity is achieved when the slope of dispersion curve become zero, *i.e.* near the Γ point the group velocity of light becomes zero ($dw/dk \rightarrow 0$), thereby leading to the formation of a stable and large single-cavity mode. The mode profile is simulated and shown in Fig. 3(a). The mode intensity is mostly distributed in the nanocrystals. The extremely low group velocity leads to the long interaction time between radiation field and active material and consequently gives rise to a strong gain enhancement.

InGaN nanowire surface-emitting laser diodes were fabricated using planarization, polyimide passivation, contact metallization, and photolithography techniques. Shown in Fig. 3(b) is a representative current-voltage (I-V) curve of the device, which clearly shows rectification characteristics with a sharp turn-on voltage of ~3.3 V at room temperature. The device exhibited excellent I-V characteristics, which is partly due to the significantly reduced defect density and enhanced dopant incorporation in nanowire structures. The electroluminescence characteristics were measured under CW biasing conditions at room temperature. Figure 3(c) shows the electroluminescence spectra of the laser measured under different injection currents. At low injection current density of ~200 A/cm^2, the device exhibits a broad emission spectrum centered at ~524 nm, with a full-width-at-half-maximum (FWHM) ~30 nm, which corresponds to the spontaneous emission of the multiple quantum disk active region. A sharp lasing peak at ~523.1 nm wavelength was observed with increasing injection current. The strong lasing spot is shown in the inset of Fig. 3(b). Variations of the output power vs. injection current were further measured, which exhibits a clear threshold at ~400 A/cm^2.

In summary, we have demonstrated a surface-emitting laser diode by utilizing bottom-up InGaN nanowire arrays. Compared to the conventional GaN VCSELs, lasing and surface emission is achieved without using thick, resistive, and often heavily dislocated DBRs. This unique laser concept can be readily extended to achieve monolithic surface-emitting laser diodes operating across the entire visible, as well as mid and deep UV wavelengths, and to realize such lasers on low cost, large area Si wafers. Our studies therefore open a new paradigm in the design and development of surface-emitting laser diodes, wherein the performance is no longer limited by the availability of DBRs, lattice mismatch, and substrate availability.

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